Dynamical Distribution of Zero Vector of DTC Method of PMSM

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Abstract

In order to improve the efficiency of the electrical vehicles driving by constant Magnet synchronous motor (PMSM), the paper applies a space vector modulation strategy for the new dynamic allocation of zero-vector which is aiming at reducing the inverter switching losses; It obtains the switching frequency of power tube in dynamic-state and steady-state basing on speed error, in order to reduce inverter switching losses; It applies the maximum torque/current control method , according to which the flux value was adjusted. The simulation results shows that, comparing with the traditional DTC system, the very method can raise the system efficiency on the premise of keeping in lower speed function.

Keywords

Electrical Vehicle; Direct Torque Control; Switching Losses; Maximum Torque/Current Control

Introduction

The traditional torque control applied a hexagon flux orbit control method for torque control and flux control of motor which adopted a controller of Transfer matrix and flux Hysteresis loop and choose the Voltage vector from the prefabricated switch value table. However, it has flaws as follows[1]: The low speed is not ideal, the Switching frequency is not constant, and the torque pulsation is a little big; The flux has a frequent distortion; it can not control the torque and flux at the same time. Though torque pulsation is not an outstanding problem for the electrical vehicles, the instable and fluctuation range of switching frequency caused by fixed loop width will bring out flaws as : preventing the power device capacity being brought into full play, the slowing down of the adjusting function of torque and system efficiency. And as to the drive system that applied as the core technology of electrical vehicles, the high efficiency is one of the important indexes.

In order to solve the above problems, the paper[2] is to obtain the hysteresis loop width of comparator for torque and hysteresis loop by applying the PI conditioner for the Switching frequency of Inverter. The given SVM-DTC modulation is not necessary to make complicated Polar coordinate transformation, which aiming at slowing down the torque pulsation and losses[3].

As the Zero vector having the function of keeping the torque invariable when used in PMSM, it has an effective restrain for the pulsation of flux and torque , an improvement for the system's steady running state, and can make the system keep a fast dynamic response[4]. As a fact of that, the different choosing methods of the distribution method of Zero vector for the PWM wave of space vector and non zero -vector can cause various PWM wave of voltage space vector. For example, the paper[5] achieves the stable switching frequency of power device by the combination of Fuzzy neural network and the adjustment of voltage vector. The paper[6] draws in a simple SVM method, and gives an explicit calculation method of flux vector, which can keep a stable switching frequency of power device. However, as to motor, it doesn't separate the working frequency of steady-state and transient-state when applying a higher steady switching frequency to achieve the circle flux, which will bring a higher switching frequency and losses when under steady-state.

In order to lift the system efficiency, the paper makes some improvement to the traditional control method. From the view of slow down the losses of switching, it draws in a new dynamic distribution technology of zero vector, and alter the switching frequency during the speed changing actively pointing to kinds of work situation, this will have achieved a low losses of devices and a direct torque control for maximum torque\current of PMSM under base speed.

An Improved Voltage Space Vector Control

The reason for applying SVM is to composing the required reference voltage vector with the original 8

basic voltage space vector in inverter(as the Fig.1). Fig.1 also gives the achieving way of SVM in Sector 1. Supposing that TPWM-=t1+t2+t0 is the circle of system PWM, t0,t1,t2 is the action time of every voltage vector in each circle separately, θis the reference voltage. In case of Sector 1, t1,t2 can be showed as:

$$t_1 = \frac{2U_{out}}{\sqrt{3}U_1} T_{PWM} \sin(60^\circ - \theta) \quad (1)$$

$$t_2 = \frac{2U_{out}}{\sqrt{3}U_2} T_{PWM} \sin\theta \quad (2)$$

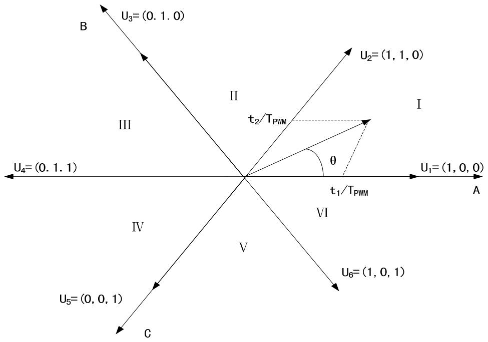


FIG.1 SCHEMATIC OF SYNTHETIC REFERENCE VOLTAGE VECTOR

As to the popular seven sections of symmetrical type SVM, in each circle, PWM Wave is composed with 3 zero vector and 4 non zero vector, 3 sections of zero vector is placed in the beginning、middle and end of the wave separately. In this sector, the voltage is exerted in order of (000),(100),(110),(111),(110),(100),(000), the working time is t0/4,t1/2,t2/2 ,t0/2,t2/2,t1/2,t0/4 in turn. In other sectors, the composing of the required space vector can be deduced by analogy. From the above, we can see that the change between a nearly two voltage space vectors can only be a switching pipe action of a bridge arm. And in each PWM circle, the switching number of switching pipe is all the same. This method can not only raise the bus's utilization rate, but also control the switching frequency of power device.

However, the overlapping of voltage and current exits during the whole switching actions, the raising of calorific value of switching device can increase the switching losses. Though this control mode can restrain the low harmonic in voltage wave effectively, it will bring the flaws as: the causing of some large amplitude high harmonic will make a grow up of the voltage peak value and a raising up of the inside eddy current and skin effect, which may cause an increase of the motor temperature and cut down the service life.

It is showed in the voltage space vector in Fig.1 that whatever the distribution of zero vector in each sector is, it can only make sure a phase of bridge arm stay in non-switching state, or two bridge arms in the same sector can not stay in non-switching state at the same time. That's to say, when under symmetrical three-phase condition, non-switching state sector had by each phase of bridge arm can't beyond 120。.

The switching losses has relevant with the numbers of switching actions and the current, the cutting down of the switching action can't low down the losses because of the large current caused during the switching action. So, there is a requirement to cut down the switching number to make sure the current as small as possible, which will slow down the switching losses.

As a matter of that, if we can make sure that the very phase bridge arm isn't conduction when each current phase reaching its maximum value, the losses will get down an low as possible. As each phase of current vector in PMSM lagging the voltage one and the principle of direct torque control making sure that every reference voltage vector and composing current vector in each circle can not always in the same sector, in the control process, each tested phase current get the sector where it's composed, according to which it redistributes the zero vector used in the sector.

As the zero vector can only change the flux's changingspeed but the shape of flux circle, and in order to make the switching number of pipe reach the least in each circle, we redistribute the zero vector in each sector. The rule is to make each phase of bridge arm have no conduction in the peak value of phase current, the specific distribution method is showed as Tab.1:

TABLE 1 THE DISTRIBUTION OF ZERO VECTOR OF EACH SECTOR

合成电流位置	扇区					
	Ⅰ	Ⅱ	Ⅲ	Ⅳ	Ⅴ	Ⅵ
Ⅰ，Ⅳ	U_7	U_0	U_0	U_0	U_7	U_7
Ⅱ，Ⅴ	U_0	U_0	U_7	U_7	U_7	U_0
Ⅲ，Ⅵ	U_7	U_7	U_7	U_0	U_0	U_0

W

When the composed current stay in Sector I and Ⅳ, the amplitude of A phase positive current and C phase opposite current is larger, to make sure the action of bridge arm of A phase and C phase as less as possible. In Sector Ⅱ,Ⅲ and Ⅳ, if we chooses the zero vector as U0(0,0,0), and then in Sector Ⅱ,C phase keep the state as upper arm conducting and lower arm cutting off, in Sector Ⅲ,Ⅳ, A phase keep the state as upper arm

cutting off and lower arm conducting; if we choose zero vector as U7(1，1，1) in Ⅳ，Ⅴ，Ⅰ, then in Sector Ⅴ, C phase keep the state as upper arm conducting and lower arm cutting off, and in Sector Ⅰ，Ⅵ, A phase keep state as upper arm conducting and lower arm cutting off. When it's in Sector Ⅱ、Ⅴand Ⅲ、Ⅵ, the phase current between B,C and B,A is larger. According to the above, the distribution mode of zero-vector can be given.

The Direct Control of PMSM Basing on the Least Switching Losses

System Structure

Fig.2 is the Schematic diagram of direct control of PMSM basing on the least switching losses. The speed error signal obtains the given torque after the torque conditioner's handling, giving the difference value between the given torque and real torque, and then gives the Phase angle increment of given flux after the dealing of PI conditioner. As the switching losses of device relates the system efficiency directly, it establishes the circle conditioner of given PWM circle with the speed error as the import, in order to adjust the system's device switching frequency under steady-state and dynamic-state. As a matter of that, system can obtain the parameters as the flux phase angle and amplitude increment、given switching frequency 、flux observed signal, and the reference voltage vector from the control PC. At last, system obtains the control signal of each phase through SVPWM modular, with which the inverter controls the PMSM.

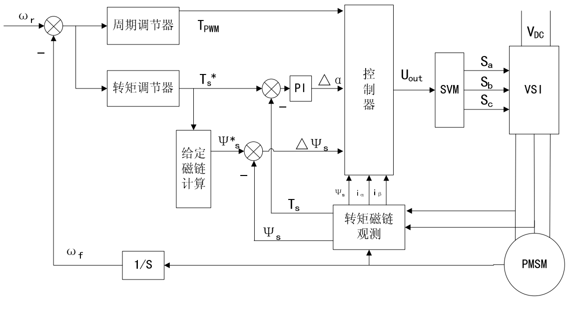


FIG. 2 DIRECT TORQUE CONTROL SCHEMATIC OF PMSM

The Calculation of Reference Voltage Space Vector

As the Fig.3 showed, in 2 phase stationary coordinate system, taking the first quadrant for example(the calculation process of reference vector in other quadrants), in one switching circle, it's required the stator flux linkage change from Ψ toΨ' , the phase angle has corresponding changed in △a, and then the changing volume of stator flux linkage is:

$$\Delta\Psi_s = \Psi_s^* - \Psi_s \tag{3}$$

Calculate the separate quantity of Stator flux linkage's difference value in stationary coordinate system:

$$\Delta\Psi_{s\alpha} = \left|\Psi_s^*\right|\cos(\alpha+\Delta\alpha) - \Psi_{s\alpha} \tag{4}$$

$$\Delta\Psi_{s\beta} = \left|\Psi_s^*\right|\sin(\alpha+\Delta\alpha) - \Psi_{s\beta} \tag{5}$$

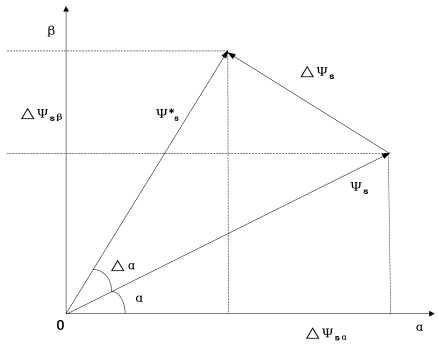


FIG.3 THE VARIETY OF THE STATOR FLUX

And $$\alpha = \arctan\left(\frac{\Psi_{s\beta}}{\Psi_{s\alpha}}\right) \tag{6}$$

Stator flux linkage can be calculated :

$$\Psi_{s\alpha} = \int (U_{s\alpha} - r_s i_{s\alpha})dt \tag{7}$$

$$\Psi_{s\beta} = \int (U_{s\beta} - r_s i_{s\beta})dt \tag{8}$$

In the equation, r_s is stator resistance.

According to the stator equation in stationary coordinate system and Formula (1)、(2), the separate quantity of reference voltage vector in stationary coordinate system can be calculated:

$$U_{s\alpha}^* = r_s i_{s\alpha} + \frac{\Delta\Psi_{s\alpha}}{T_{PWM}} \tag{9}$$

$$U_{s\beta}^* = r_s i_{s\beta} + \frac{\Delta\Psi_{s\alpha}}{T_{PWM}} \tag{10}$$

The reference voltage vector can be calculated:

$$\left|U_{out}\right| = \sqrt{(U_{s\alpha}^*)^2 + (U_{s\beta}^*)^2} \tag{11}$$

$$\theta = \arctan\left(\frac{U_{s\alpha}^*}{U_{s\beta}^*}\right) \tag{12}$$

Conditioner of PWM Circle

As to the direct torque control, applying circle flux

orbit can solve the torque pulsation effectively, however, a relatively high switching frequency of inverter will cause a large switching losses[7]. As a large inertia load characteristic of electrical vehicles, the key is to improve efficiency, the smaller torque pulsation is not the principal contradiction. So, when system is in dynamic, a larger switching frequency, which is lower in steady-state, is required to lift the speed.

$$T_{PWM}(k) = k_p \Delta\omega(k) + k_i \sum_{j=0}^{k} \omega(j)T \tag{13}$$

In formula, K_P is proportional coefficient, K_I is integral coefficient, Oco(k) is rotational speed error. T is system sample error.

Considering the limit of maximum frequency of inverter and system's low speed property, it's required to limit the amplitude of PWM circle inverter.

The Given Flux

As to PMSM, different stator flux linkage gives different maximum torque, for the keeping of given flux value and maximum torque obtaining by running, enough stator current is required, and the motor must run in terms of MTPA mode. So, establish flux setter according to the MTPA equation[8] basing on direct torque control of PMSM.

$$\Psi_f i_d + (L_q - L_d)(i_q^2 - i_d^2) = 0 \tag{14}$$

$$T = 1.5 n_p \sqrt{i_d^2 - \Psi_f i_d [\Psi_f (L_q - L_d) i_d] / (L_q - L_d)} \tag{15}$$

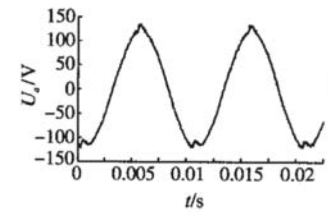
$$\Psi_s = \sqrt{(L_d i_d + \Psi_f)^2 + (L_q i_q)^2} \tag{16}$$

The required direct axis current and quadrature axis current can be calculated by the given torque on formula (7)、(8), and so as to the given flux value according to formula (9). We can see that when $L_d = L_q$, it's a control mode for i_d =0. This MTPA control mode can keep the least stator current with the same torque, and cut down the corresponding copper loss.

Researching on Simulation

Research on a PMSM system of voltage source inverter, the motor parameter is: motor pole pairs number is 4, rotor flux is 0.1194 Wb, stator resistance is 0.05 Ω, rated torque is 87. 75N.m, direct axis inductance is 0.595mH, quadrature axis inductance is 1.195mH, rated speed is 3 000 r/min, supplied power voltage is 300V. Applying seven sections of symmetrical type SVPWM and an advanced method separately to research the switching losses during the system running. The time for the conducting and cutting off of the IGBT is 0.8μs and 0.4μs separately. The system sample circle is 0.1μs, when using the method, YPWN is 200μs.

The voltage wave obtained from traditional seven sections of symmetrical type SVPWM and advanced SVPWM can be showed as Fig.4 and Fig.5. From Fig.4, we can see that spike appears in the peak value of the positive of voltage, the traditional SVM modulation method can not make a full use of the capacity of inverter. However, the advanced SVM can clear the spike, which can improve the voltage capacity of inverter, and bring in corresponding harmonic waves.



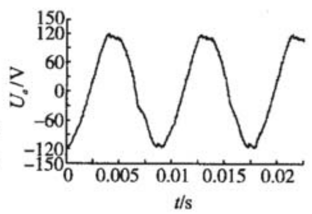
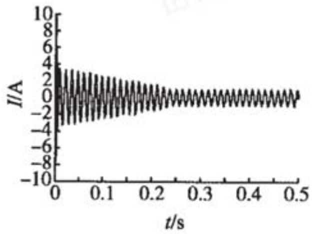


FIG. 4 VOLTAGE WAVE OF SYMMETRY

FIG. 5 IMPROVED VOLTAGESEVEN REGIONAL APPROACH WAVE OF SVPWM



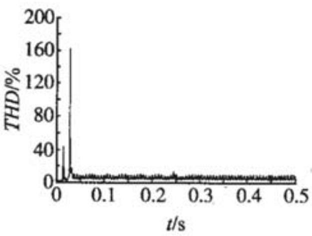
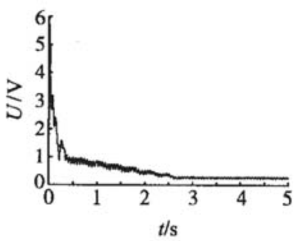


FIG. 6 CURRENT WAVEFORM

FIG. 7 CURRENT DISTORTION RATEOF STARTING PROCESS OF STARTING PROCESS



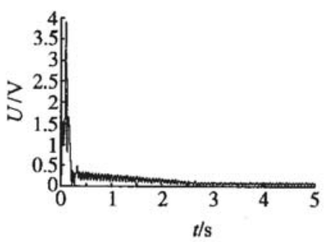


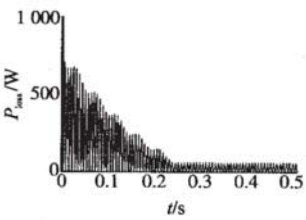
FIG. 8 THE 3RD HARMONIC CURRENT OF IMPROVED SVM MODE

FIG. 9 THE 5TH HARMONIC CURRENT OFIMPROVED SVM MODE

Fig.6 and Fig.7 are A phase current and the harmonic waves aberration rate. Fig.8 and Fig.9 are the

amplitude of 3rd harmonic waves and 5th harmonic waves. From Fig.9 we can see that the amplitude of 5th harmonic waves is low enough. In inverter's output, low harmonic is the main influence factor for motor's drive function. And the connecting of three phase motor can clear the 3rd harmonic waves in line current, without affecting the running of motor.

Fig.10 and Fig.11 shows the switching losses of running process under seven sections of symmetrical type SVPWM and an advanced method separately. From Fig.11 we can see that, the advanced SVM cut down the switching losses.



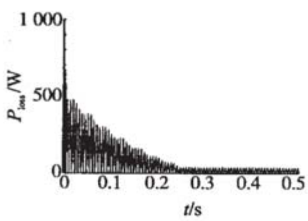


FIG. 10 COMMON MODE SWITCH LOSS OF POWER DEVICES

FIG. 11 IMPROVED MODE SWITCH LOSS OF POWER DEVICES

Conclusion

Considering the torque pulsation and system's low speed characteristic, according the special effect of zero vector, the paper applies an advanced SVM modulation mode to cut down system's switching losses; A smaller torque pulsation isn't sensitive to the load of electrical vehicles, with which the paper have designed a conditioner for PWM circle to cut down the switching number; And pointing to reduce the stator current, MTPA is applied to achieve the control of PMSM for the driving of electrical vehicles.

Comparing the simulation results with the control way of seven sections of fixed switching frequency of symmetrical type SVPWM, the paper's method is more initiative, which not only reduces harmonic waves, but also cuts down the switching losses. Today , DSP is Widely used, and the very method has a brighter application prospect than traditional DTC.

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